

Axion domain wall baryogenesis

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Abstract. We propose a new scenario of baryogenesis, in which annihilation of axion domain walls generates a sizable baryon asymmetry. Successful baryogenesis is possible for a wide range of the axion mass and decay constant, $m \simeq 10^8\text{--}10^{13}\text{ GeV}$ and $f \simeq 10^{13}\text{--}10^{16}\text{ GeV}$. Baryonic isocurvature perturbations are significantly suppressed in our model, in contrast to various spontaneous baryogenesis scenarios in the slow-roll regime. In particular, the axion domain wall baryogenesis is consistent with high-scale inflation which generates a large tensor-to-scalar ratio within the reach of future CMB B-mode experiments. We also discuss the gravitational waves produced by the domain wall annihilation and its implications for the future gravitational wave experiments.

Keywords: axions, baryon asymmetry, physics of the early universe, Cosmic strings, domain walls, monopoles

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Contents

| | | |
|----------|--|-----------|
| 1 | Introduction | 1 |
| 2 | Axion domain walls | 3 |
| 3 | Baryogenesis by domain wall annihilation | 5 |
| 3.1 | Analytical estimate of the asymmetry | 5 |
| 3.2 | Necessary conditions for successful baryogenesis | 7 |
| 3.3 | Numerical calculations | 8 |
| 3.4 | Baryonic isocurvature perturbations | 10 |
| 4 | Discussion and conclusions | 12 |

1 Introduction

Axions may be ubiquitous in nature. Indeed, there appear many axions through compactification of the extra dimensions in the string theory [1, 2]. Some of them may remain relatively light and play an important role in cosmology such as inflation, dark matter and dark energy. In this paper we shall present a new scenario of baryogenesis, in which axions play a key role.

The axion exhibits a shift symmetry,

$$a \rightarrow a + C, \quad (1.1)$$

where C is a real transformation parameter. While the shift symmetry keeps the axion potential flat at the perturbative level, non-perturbative effects break the symmetry to a remnant discrete one.

Let us suppose that one of the non-perturbative effects gives the dominant contribution to the axion potential, which is expressed as

$$V(a) \simeq m^2 f^2 \left(1 - \cos \left(\frac{a}{f} \right) \right), \quad (1.2)$$

where m is the axion mass and f is the decay constant. Then, the axion potential has a series of N (approximately) degenerate vacua, where the precise value of N depends on the details of the UV theory.¹ If the axion is lighter than the Hubble parameter during inflation, it acquires quantum fluctuations which extend beyond the Hubble horizon. For sufficiently large quantum fluctuations, some of the N vacua might be populated, which results in domain wall formation after inflation. The domain walls are cosmologically problematic, and so, they must annihilate before dominating the Universe. This is possible if the degeneracy between different vacua is lifted by other non-perturbative effects [8–11]. The domain wall annihilation and the emitted gravitational waves have been extensively studied in the literature [12–15].

¹The fact that the axion potential can have multiple approximately degenerate vacua has been exploited in context of dark energy [3] as well as inflation [4–7].

In this paper we point out that the annihilation of domain walls also induces the baryon asymmetry of the Universe. Suppose that the axion is derivatively coupled to the standard model (SM) quarks and/or leptons,

$$\mathcal{L} = \frac{\partial_\mu a}{f} j^\mu = \sum_i c_i \frac{\partial_\mu a}{f} \bar{\psi}_i \gamma^\mu \psi_i, \quad (1.3)$$

where c_i is a coupling constant. The time derivative of the axion plays a role of the effective chemical potential, which spontaneously breaks the CPT symmetry.² This enables the generation of the baryon or lepton asymmetry in thermal plasma if the baryon or lepton number is broken, and this is the so-called spontaneous baryogenesis scenario [17–20]. The current to which the axion is coupled does not have to coincide exactly with the baryon or lepton current; for instance, it could be a U(1) hypercharge current [20] or a Peccei-Quinn current [21, 22]. Such derivative couplings to the baryon and lepton currents can also be induced if the axion has an anomalous coupling to the SU(2) gauge fields [19]. In this case the chemical potential is induced by sphalerons [23, 24], because a non-zero time derivative of the axion generates energy difference between the states with different winding number and $B+L$ number. Therefore, the chemical potential is expected to be suppressed at $T \gtrsim 10^{12}$ GeV where sphalerons decouple from the cosmic expansion. Note that there is no such suppression of the effective chemical potential if one starts with the derivative couplings with baryon and/or lepton current (more precisely, $B-L$ current), as we shall do below. We shall see that, if the axion has such derivative couplings, a sizable baryon asymmetry can be generated when the axion domain walls annihilate.

Before going into details, let us give a rough sketch of our scenario. For simplicity, we assume that only two vacua, a_1 and a_2 with $a_1 < a_2$, are populated during inflation, leading to formation of domain walls separating the two vacua. Generalization to the case of multiple vacua is straightforward. After formation, domain walls randomly move around at relativistic speed, collide and annihilate continuously, so that the domain wall network show the dynamical scaling behavior [25–28]. Every time a domain wall goes through some point in space, the field value of the axion changes either from a_1 to a_2 or from a_2 to a_1 . Such transition induces a temporal and local chemical potential for baryons or leptons. No net baryon asymmetry is generated by the domain wall dynamics in the scaling regime, however, because both transitions occur with an equal probability and there is no preference of baryons over anti-baryons. The asymmetry between the two vacua becomes important when the domain walls annihilate because of the energy bias. Suppose that one of the vacua is energetically preferred, e.g., $V(a_1) < V(a_2)$. When domain walls annihilate, the value of a then decreases from a_2 to a_1 in a region of the false vacuum, which gives a preference to baryons over anti-baryons for a certain choice of the couplings. Thus, the axion domain wall annihilation can generate the baryon asymmetry of the Universe.

Our scenario has several advantages. First, it is known that the spontaneous baryogenesis in the slow-roll regime generically leads to baryonic isocurvature perturbations [29], which makes the scenario incompatible with high-scale inflation.³ In our scenario, however, the baryonic isocurvature perturbations can be significantly suppressed, because of the scaling property of the domain wall network. In particular, our scenario is consistent with large-field

²See ref. [16] for leptogenesis using explicit (non-dynamical) CPT-breaking interactions.

³It is possible to give the axion a mass of order the Hubble parameter in the spontaneous baryogenesis using a flat direction [21, 22], thus avoiding the isocurvature constraint. Also, no isocurvature perturbation is induced in the gravitational baryogenesis [30].

inflation, and therefore, the required high reheating temperature can be realized more easily. Secondly, the axion field value is kept large inside domain walls, which enables a large effective chemical potential even when the axion mass m becomes larger than the Hubble parameter. Without domain walls, the spontaneous baryogenesis would become inefficient when the axion starts to oscillate about the minimum [31]. Therefore, the axion domain wall baryogenesis scenario works for a wide range of the axion mass and the inflation scale.

Lastly let us comment on differences of our scenario from other works. In the thick-wall regime of the electroweak baryogenesis, the passage of an expanding bubble wall generates a non-zero chemical potential, which leaves net baryon asymmetry in thermal plasma based on the spontaneous baryogenesis [19, 20] (see also ref. [32]). The bubble walls play a similar role to that of domain walls in our scenario. The difference is that the electroweak spontaneous baryogenesis relies on the first order phase transition of two (or more) Higgs fields, and the sphaleron process is exponentially suppressed in the symmetry breaking vacuum. As a result, the estimate of the final baryon asymmetry requires a precise determination of the critical field value as well as detailed analysis of the diffusion process during the phase transition [33]. In our scenario, on the other hand, the baryon (or lepton) number violation is operative equally in the two minima. Also it relies on the domain wall dynamics of a single axion field, whose behavior is well studied with numerical simulations. This makes our scenario relatively simple and robust. Recently, the authors of ref. [34] proposed a scenario where the axion has only anomalous coupling to $SU(2)_L$ gauge fields. They studied a spatially homogeneous axion field in the slow-roll regime, and explored the parameter space of the axion mass and decay constant preferred by the string axions. The parameter ranges have an overlap with our scenario. One difference is that we start with derivative couplings of the axion with baryon and/or lepton currents. Another is that our scenario relies on the domain wall dynamics, while ref. [34] focused on the homogeneous axion field.

The rest of this paper is organized as follows. In section 2, we briefly review the evolution of axion domain walls. We estimate the baryon asymmetry induced by the domain wall annihilation in section 3. The last section is devoted to discussion and conclusions.

2 Axion domain walls

Let us consider an axion whose potential is given by

$$V(a) = m^2 f^2 \left(1 - \cos \left(\frac{a}{f} \right) \right), \quad (2.1)$$

where m and f are the mass and the decay constant of the axion a . We assume that two adjacent minima, $a_1 = 0$ and $a_2 = 2\pi f$, are populated with more or less equal probability during inflation, and that domain walls separating the two minima are formed after inflation. This is the case if the quantum fluctuations of the axion, $\delta a \sim H_{\text{inf}}/2\pi$, is comparable to the decay constant, or if the initial position of the axion is sufficiently close to the local maximum, $a_{\text{max}} = \pi f$. Our scenario can be straightforwardly applied to the case in which more than two minima are populated.

The domain wall solution in a flat spacetime is given by

$$a_{\text{dw}}(t, \vec{x}) = 4f \tan^{-1} \exp [m\gamma(x - vt)], \quad (2.2)$$

where x is the spatial coordinate perpendicular to the domain wall, v is the domain wall velocity and γ is the relativistic factor defined by $\gamma = 1/\sqrt{1 - v^2}$. The above solution is

valid if the thickness of the domain wall $\sim m^{-1}$ is much smaller than the Hubble horizon, i.e., $m \gg H$, where H is the Hubble parameter. The energy density of the domain wall is characterized by the tension σ ,

$$\sigma = 8mf^2, \quad (2.3)$$

for the potential (2.1).

The domain walls are formed when $H \simeq m$. According to the numerical and analytic calculations [25–28], within a few Hubble time after the formation, the domain walls quickly follow the scaling law, i.e.,

$$\rho_{\text{dw}} \sim \sigma H, \quad (2.4)$$

where there are only one or a few domain walls in each Hubble horizon. The domain walls must annihilate and disappear before they start to dominate the Universe, since otherwise the Universe would be too inhomogeneous. We assume that there is another shift-symmetry breaking term which generates a bias between the two minima, $\epsilon \equiv V(a_2) - V(a_1)$. Then domain walls annihilate rapidly when the energy density of domain walls becomes comparable to the energy bias [9–11],

$$\rho_{\text{dw}} \sim \epsilon. \quad (2.5)$$

Marginally relativistic axion particles with a typical momentum, $k \sim m$, are copiously produced through the axion domain wall annihilation. Those axion particles soon become non-relativistic due to the cosmic expansion [13–15]. In addition, axion coherent oscillations are produced at the domain wall formation, and we shall discuss their cosmological impact later in this paper.

The axion particles eventually decay into SM particles through their couplings with the SM sector. In general, the axion can have derivative couplings to fermions like (1.3), which are allowed by the shift symmetry (1.1). Specifically we focus on the case in which the axion has derivative couplings only to the SM left-handed lepton currents,⁴

$$\mathcal{L} \ni \frac{\partial_\mu a}{f} \sum_{i=e,\mu,\tau} \bar{L}_i \gamma^\mu L_i \equiv \frac{\partial_\mu a}{f} j^\mu. \quad (2.6)$$

Our results remain practically unchanged even if one adds additional derivative couplings to other SM fermions. If the axion is coupled to the SM sector only through the above interaction (2.6), it mainly decays into a pair of $\text{SU}(2)_L$ gauge bosons and hypercharge gauge bosons through its anomalous couplings [17, 18]. The decay width into a pair of gauge bosons is approximately given by

$$\Gamma_a \simeq \left(\frac{3\alpha_2^2}{256\pi^3} + \frac{\alpha'^2}{1024\pi^3} \right) \frac{N_f^2 m^3}{f^2}, \quad (2.7)$$

where α_2 and α' are respectively $\text{SU}(2)_L$ and $\text{U}(1)_Y$ gauge coupling constants and N_f is the number of generation, and we will set $N_f = 3$ in the following. Approximating that this is the main decay channel, the axion decay temperature is

$$T_a \simeq 3 \times 10^7 \text{ GeV} \left(\frac{m}{10^{11} \text{ GeV}} \right)^{3/2} \left(\frac{10^{15} \text{ GeV}}{f} \right), \quad (2.8)$$

⁴In a supersymmetric theory, this type of coupling arises from the Kähler potential $K = \frac{1}{f}(\mathcal{A} + \mathcal{A}^\dagger)L^\dagger L$, where \mathcal{A} and L are respectively the axion and the lepton supermultiplet, and the lowest component of \mathcal{A} is given by the saxion and axion as $\mathcal{A} = s + ia$.

where we have defined the decay temperature by $3H(T_a) = \Gamma_a$. If those axion particles dominate the Universe before the decay, there will be an extra entropy production by the axion decay, which dilutes pre-existing baryon asymmetry by some amount. As we shall see, the entropy dilution becomes important for a large decay constant and a small axion mass.

3 Baryogenesis by domain wall annihilation

3.1 Analytical estimate of the asymmetry

Now let us discuss baryogenesis by the axion domain walls under the existence of the derivative coupling to the lepton current given by (2.6).⁵ As previously noted, if \dot{a} is non-vanishing, the derivative couplings behave like an effective chemical potential,

$$\frac{\partial_\mu a}{f} j^\mu = \mu_{\text{eff}} j^0 + \dots, \quad (3.1)$$

where $\mu_{\text{eff}} = \dot{a}/f$ is the effective chemical potential for the lepton number (L).

The axion domain walls can generate the effective chemical potential because of the large spatial gradient of the axion field inside the wall. Since domain walls are moving at nearly the speed of light, the time derivative of the axion field at some fixed spatial point becomes large while domain walls are passing through. The effect of the gradient term is negligible if the domain wall is sufficiently thick compared to the diffusion length.

If the L -number violating operator is in equilibrium, and if the chemical potential is spatially homogeneous, the difference of number densities between lepton and anti-leptons would be produced as $n_\ell^{\text{eq}} - n_{\bar{\ell}}^{\text{eq}} \simeq 2\mu_{\text{eff}} T^2$ for $\mu_{\text{eff}} \ll T$, where we have taken into account the spin degrees of freedom and the number of generation. It depends on the rate of the L -number violating process as well as the domain wall dynamics whether the lepton asymmetry reaches the equilibrium value in the expanding Universe. One needs to solve the Boltzmann equation for the lepton asymmetry, $n_L = n_\ell - n_{\bar{\ell}}$,

$$\dot{n}_L + 3Hn_L = -\Gamma (n_L - n_L^{\text{eq}}), \quad (3.2)$$

where Γ is the interaction rate for the L -violating processes. Note here that the chemical potential in n_L^{eq} depends on the position and velocity of domain walls.

As the L -number violating operator, we consider $\Delta L = 2$ scattering processes, $\ell\ell \leftrightarrow HH$, $\ell H \leftrightarrow \bar{\ell}\bar{H}$, which are mediated by heavy right-handed Majorana neutrinos in the seesaw mechanism [35–38]. Here and in what follows we assume that the right-handed neutrinos are so heavy that they can be integrated out in our analysis. The interaction rate for the $\Delta L = 2$ processes is roughly given by [39]

$$\Gamma \sim \frac{T^3}{\pi^3} \frac{\sum m_i^2}{v_{\text{EW}}^4}, \quad (3.3)$$

where $v_{\text{EW}} = 174 \text{ GeV}$ and m_i with $i = 1, 2, 3$ denotes the mass of three active neutrinos. The decoupling temperature of the L -violating process in the radiation dominated Universe is

$$T_{\text{dec}} \sim 3 \times 10^{13} \text{ GeV}, \quad (3.4)$$

⁵Instead, one may use an anomalous coupling of the axion to the $\text{SU}(2)$ gauge fields, in which the baryogenesis works similarly as long as the sphalerons are in equilibrium at the domain wall annihilation. (See the discussion in section 1).

where we have assumed the normal ordering for the neutrino mass differences and used the experimental value, $\sum m_i^2 \simeq \Delta m_{\text{atm}}^2 \simeq 2.4 \times 10^{-3} \text{ eV}^2$. For the reheating temperature T_R lower than T_{dec} , the L -violating process remains decoupled from the cosmic expansion. As we shall see below, even in this case, a non-zero lepton asymmetry is induced by the domain wall annihilation.

Let us first consider an ideal situation where a domain wall passes through the origin $\vec{x} = 0$ at $t = t_{\text{DW}}$. Using eq. (2.2), the effective chemical potential at the origin evolves with time as

$$\mu_{\text{eff}} = -\frac{2m\gamma v}{\cosh[m\gamma v(t - t_{\text{DW}})]}. \quad (3.5)$$

It takes roughly $\Delta t \sim (m\gamma v)^{-1}$ for the domain wall to pass through the origin, and so, the induced lepton asymmetry by passage of the domain wall is estimated as

$$n_L \simeq \Gamma n_L^{\text{eq}} \Delta t \sim \Gamma T^2. \quad (3.6)$$

Note that the lepton asymmetry becomes independent of the velocity of the domain walls. As the domain wall passes through, a similar amount of the lepton number density will be induced inside the Hubble horizon.

In the scaling regime, domain walls randomly move around inside the Hubble horizon so as to collide and annihilate continuously. In particular, since there is no preference for either of the vacua, the effective chemical potential can be positive or negative with equal probability. Therefore there will be no net lepton asymmetry left, even though some amount of the lepton asymmetry with either positive or negative sign is induced each time a domain wall passes through. Such lepton asymmetry has fluctuations of order unity inside the Hubble horizon, but it has no sizable fluctuations at superhorizon scales, because of the scaling property of the domain-wall network.

A non-zero net lepton asymmetry is induced when domain walls annihilate and disappear owing to the energy bias. This is because one of the two vacua is energetically preferred, inducing an effective chemical potential with a fixed sign in the false vacuum which occupies about half of the space. Again, the scaling property of the domain wall network ensures that there is no isocurvature perturbations at super-horizon scales.

The final lepton asymmetry is generated within about one or a few Hubble time before the domain wall annihilation. In particular, the maximal possible value of the lepton asymmetry is obtained when the domain wall annihilation takes place at the decoupling of the L -violating processes. The reason is as follows. If the domain wall annihilation takes place before the decoupling of the L -violating processes, the lepton asymmetry induced by the domain wall annihilation will be washed out. On the other hand, if the domain wall annihilation occurs after the decoupling, the induced asymmetry tends to be suppressed because the L -violating process is inefficient. The maximum asymmetry is therefore

$$\left. \frac{n_L}{s} \right|_{\text{max}} \simeq -\frac{45}{\pi^2 g_{*s}} \left. \frac{\Gamma}{T} \right|_{\text{dec}} \sim -10^{-6}, \quad (3.7)$$

where s and g_{*s} are respectively the entropy density and the relativistic degrees of freedom. We have substituted $g_{*s} = 106.75$ and the decoupling temperature (3.4) in the second equality, assuming the radiation-dominated Universe. The negative sign is inserted in the second equality to obtain positive baryon asymmetry through sphalerons.

If the reheating temperature T_R is lower than the decoupling temperature T_{dec} , the interaction rate for the L -violating processes never exceeds the expansion rate of the Universe.

One can see this by noting that Γ/H reaches the maximal value (smaller than unity) at the reheating as long as the temperature of the dilution plasma obeys $T \sim (HT_R^2 M_P)^{1/4}$ before the reheating. Hence the maximal asymmetry in this case is obtained if the domain wall annihilation occurs at the reheating, and it is roughly given by

$$\left. \frac{n_L}{s} \right|_R \simeq \left. \frac{n_L}{s} \right|_{\max} \left(\frac{T_R}{T_{\text{dec}}} \right)^2. \quad (3.8)$$

We shall see later in this section that the maximal asymmetry is indeed generated if the domain wall annihilation takes place at $T = \min[T_{\text{dec}}, T_R]$.

3.2 Necessary conditions for successful baryogenesis

Here let us discuss some necessary conditions for the successful domain wall baryogenesis. First, the domain wall dynamics should have negligible back reaction from the generated lepton asymmetry in the plasma. As the domain walls move in the plasma, some amount of the lepton asymmetry is induced because of the effective chemical potential (3.5). The interaction with the generated asymmetry induces a back reaction, which would act as a frictional force on the domain wall dynamics. The back reaction is negligible, and the domain walls follow the scaling law if

$$\sigma H \gtrsim \mu_{\text{eff}} n_L \quad (3.9)$$

at the domain wall formation ($H_{\text{form}} \sim m$), where n_L is given by (3.6).

Secondly, the domain wall must be sufficiently thick to justify our analysis where we have neglected dissipation of the asymmetry. The thickness of the wall is roughly m^{-1} and the typical mean free path of the particle in plasma is of order T^{-1} . Thus, the thick-wall condition is given by

$$T_{\text{ann}} > m, \quad (3.10)$$

where T_{ann} denotes the temperature at the domain wall annihilation.

Thirdly, we have assumed that the domain wall annihilation takes place well after the domain wall network start to follow the scaling law. It takes a few Hubble time after the formation to reach the scaling regime, and therefore we conservatively require

$$H_{\text{form}} \sim m > 10H_{\text{ann}}, \quad (3.11)$$

where H_{form} and H_{ann} are the Hubble parameter at the domain wall formation and annihilation, respectively.

Fourthly, we require that the decay constant is larger than the quantum fluctuations of the axion to ensure the validity of analysis using the potential (2.1). Specifically, we impose a lower bound on f as

$$f \gtrsim \frac{H_{\text{inf}}}{2\pi}, \quad (3.12)$$

where H_{inf} is the Hubble parameter during inflation. If this bound is not satisfied, the corresponding U(1) symmetry may be restored, or the saxion field may be destabilized.

Finally we assume that there is (effectively) only single path connecting the two vacua a_1 and a_2 . Apparently this is not satisfied if a U(1) symmetry is explicitly broken down to Z_2 . In this case there are two paths (clockwise and counter-clockwise) connecting the two vacua. In other words, there appear two kinds of domain walls with the same number. This can be understood by noting that the two types of the domain walls are attached to cosmic strings associated with the spontaneous break down of the U(1) symmetry. If the tensions of the two type of domain walls are equal, they would start to annihilate at the same time and

sweep equal spatial volume with positive and negative chemical potential, resulting in no net baryon asymmetry. On the other hand, if there is an explicit breaking of the Z_2 symmetry such that one type of domain walls has a larger tension than the other one, the domain walls with a smaller tension would start to annihilate first by the energy bias between the two vacua and sweep a larger spatial region, producing a net baryon asymmetry. Therefore, our scenario works even if there are multiple paths connecting the two vacua (namely if there are multiple types of domain walls), as long as one of the multiple paths is energetically favored. If there are multiple vacua, or if the symmetry is non-linearly realized, our scenario works by a similar argument.

In the numerical calculations we impose the above conditions to ensure successful domain wall baryogenesis. It turns out that all the conditions are easily satisfied for the parameters of our interest.

3.3 Numerical calculations

The net lepton asymmetry is effectively induced by the domain wall annihilation, during which domain walls sweep typically about a half of the space. To model the domain wall dynamics during the annihilation, we approximated the situation by a single domain wall passing through the origin, where we numerically solve the Boltzmann equation (3.2), combined with the evolution equations for the energy density of the inflaton (ρ_I) and radiation (ρ_r),

$$\dot{\rho}_I + 3H\rho_I = -\Gamma_I\rho_I, \quad \rho_r + 4H\rho_r = \Gamma_I\rho_I, \quad (3.13)$$

where Γ_I is the decay rate of the inflation, and we define the reheating temperature in our analysis by $3H(T_R) = \Gamma_I$. This approximation is valid because no net asymmetry is induced during the scaling regime, and so, we can focus on the domain wall dynamics during the one or a few Hubble time before the annihilation.

In figure 1 we show the induced lepton asymmetry as a function of the domain wall annihilation temperature for various values of the reheating temperature. In the left and right panels, we have set the axion mass to be $m = 10^{11}$ GeV and 10^{12} GeV, respectively. Here we have not taken into account the entropy production by the subsequent axion decay, which we shall return to in a moment. As expected, the maximal asymmetry is obtained when $T_{\text{ann}} \simeq \min(T_{\text{dec}}, T_R)$, in good agreement with the analytic estimate (3.7). In the right panel, one can see that the lepton asymmetry is highly suppressed in the case of e.g. $T_{\text{ann}} > T_{\text{dec}}$ and $T_R = 10^{14}$ GeV. This is because the asymmetry induced by the domain wall annihilation is subsequently washed out by the L -number violating processes in equilibrium. In general, we expect that the wash-out process is efficient when $T_R > T_{\text{ann}} > T_{\text{dec}}$.

At the domain wall annihilation, marginally relativistic axions are copiously produced, and they may come to dominate the Universe before they decay into gauge bosons. Once the axion dominates the Universe, its subsequent decay produces a large entropy, diluting pre-existing asymmetry. Thus, the final baryon asymmetry is fixed after the axion decay, if there is entropy dilution. Taking into account the sphaleron process,⁶ the resultant baryon asymmetry is estimated as

$$\frac{n_B}{s} \simeq -\frac{28}{79} \times \frac{1}{2} \times \Delta \times \frac{n_L}{s} \quad (3.14)$$

⁶We have neglected the sphaleron effects during the domain wall annihilation, for simplicity. This approximation is valid for most of the parameters of our interest, because, as we shall see, successful baryogenesis requires $T_{\text{ann}} \gtrsim 2 \times 10^{11}$ GeV, while the sphalerons are decoupled at $T \gtrsim 10^{12}$ GeV. Even if sphalerons are in equilibrium at the domain wall annihilation, the resultant baryon asymmetry changes only by a factor of $\mathcal{O}(1)$, and our main results remain valid.

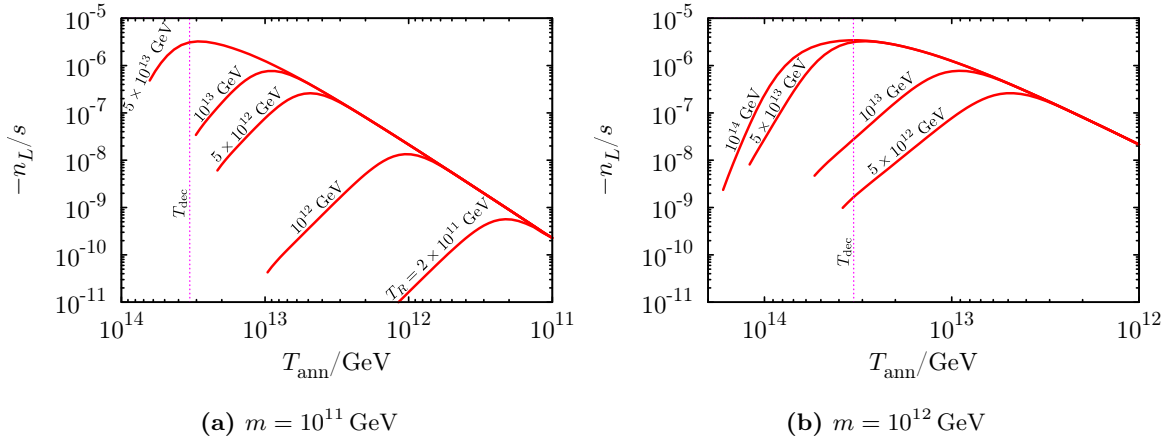


Figure 1. The induced lepton asymmetry as a function of the domain wall annihilation temperature for various values of T_R and the axion mass $m = 10^{11}$ GeV (left) and 10^{12} GeV (right). The vertical dotted (magenta) line represents the decoupling temperature of the L -number violating processes in a radiation-dominated Universe. Note that the subsequent entropy dilution by the axion decay is not taken into account here. We have imposed the condition (3.11), $m > 10H_{\text{ann}}$, which corresponds to the left end point of each curve.

where Δ is the dilution factor by the axion decay given by

$$\Delta = \begin{cases} \min\left(1, \frac{T_a H_{\text{ann}} M_P^2}{T_R \sigma}\right) & \text{(DW annihilation before reheating)} \\ \min\left(1, \frac{T_a s(T_{\text{ann}})}{\sigma H_{\text{ann}}}\right) & \text{(DW annihilation after reheating).} \end{cases} \quad (3.15)$$

The numerical factor $1/2$ comes from the fact that the transition from the false vacuum to the true vacuum takes place in about half of the whole space.

In figures 2 and 3 we show the contours of the final baryon asymmetry, n_B/s , in the m - f plane for various values of T_R . Here we have set $T_{\text{ann}} = \min(T_{\text{dec}}, T_R)$ so that the baryon asymmetry takes the largest possible value for a given reheating temperature. The baryon asymmetry can be suppressed by either increasing or decreasing T_{ann} (see figure 1a). One can see that a sufficient amount of baryon asymmetry, $n_B/s \gtrsim 10^{-10}$, can be generated for $T_R \gtrsim 2 \times 10^{11}$ GeV. In the lower shaded (magenta) region, there is no entropy dilution, i.e., $\Delta \simeq 1$, and so, n_B/s takes a constant value. As f becomes large, n_B/s decreases owing to the entropy dilution factor $\Delta \ll 1$. This is because, as f increases, the energy density of the axion particles increases and the lifetime of the axions becomes longer. The horizontal dashed (green) lines and dash-dotted (cyan) lines represent the lower bound on the axion decay constant, $f \gtrsim H_{\text{inf}}/2\pi$, for $H_{\text{inf}} = 10^{14}$ GeV and $\sigma H > \mu_{\text{eff}} n_L|_{H=m}$, respectively (cf. (3.9) and (3.12)). The yellow-shaded region in upper right corner in figure 3 is ruled out from the domain wall domination at annihilation. Below the dotted (blue) line, baryonic isocurvature perturbations and their non-Gaussianity would exceed the observational bound, if the L -number violating rate (3.3) is valid at the domain wall formation. In other words, in the region slightly below the dotted (blue) line, baryonic isocurvature perturbations and their non-Gaussianity may be found in the near future observations. We will discuss this issue in the next subsection.

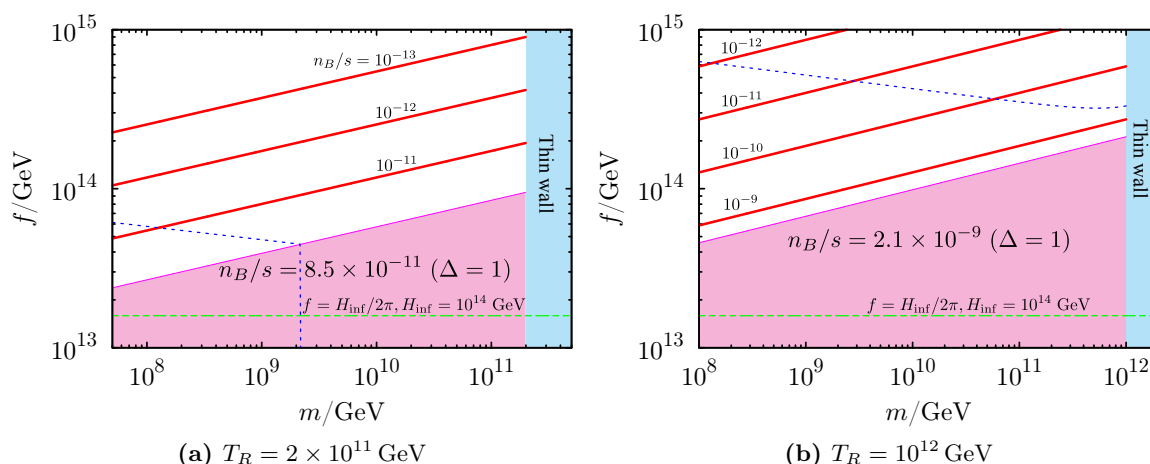


Figure 2. Contours of the final (maximal) baryon number asymmetry in the m - f plane for $T_R = 2 \times 10^{11}$ GeV (left panel) and 10^{12} GeV (right panel). We assume $T_{\text{ann}} = \min[T_R, T_{\text{dec}}]$ so that the baryon asymmetry becomes maximal. The solid (red) lines correspond to the contours of $n_B/s = 10^{-13}$ – 10^{-9} from left to right. In the shaded (magenta) regions, there is no entropy dilution (i.e. $\Delta = 1$), and n_B/s takes a constant value $n_B/s = 8.5 \times 10^{-11}$ (left panel) and 2.1×10^{-9} (right panel). In the cyan-shaded region, the thick wall condition is violated. Baryonic isocurvature perturbations and their non-Gaussianity will be too large below the dotted (blue) line, as long as one extrapolates the L -violating interactions to the domain wall formation. See the text for discussion on this issue. The horizontal dashed (green) lines represent the lower bound on f , $f > \delta a \sim H_{\text{inf}}/2\pi$ for $H_{\text{inf}} = 10^{14}$ GeV.

3.4 Baryonic isocurvature perturbations

Here we discuss baryonic isocurvature perturbations in our scenario. Here we do not distinguish lepton asymmetry and baryon asymmetry, as we are concerned with the final baryon asymmetry at the CMB epoch. First, let us consider baryon asymmetry generated by the domain wall annihilation, $Y_{\text{DW,ann}} \equiv n_B/s|_{\text{DW,ann}}$. As domain walls are spatially localized objects, $Y_{\text{DW,ann}}$ has initially large spatial fluctuations of order unity at subhorizon scales. Such small-scale fluctuations asymptote to zero in the course of evolution, because of diffusion processes of quarks and leptons. At super-horizon scales (e.g. the CMB scales), on the other hand, $Y_{\text{DW,ann}}$ has no isocurvature fluctuations because of the scaling property of the domain wall network. This results stand in sharp contrast to the usual spontaneous baryogenesis in the slow-roll regime [29].

Secondly, we turn to baryon asymmetry generated right after the domain wall formation. We have assumed that the axion acquires sufficiently large quantum fluctuations during inflation so that the two adjacent vacua are realized randomly in each Hubble horizon. This leads to the formation of domain walls when the Hubble parameter becomes comparable to the axion mass, $H \sim m$. At the same time, the axion coherent oscillations are induced. The dynamics of axion coherent oscillations, especially its motion in the slow-roll regime, generates the baryon asymmetry in the background thermal plasma as in the usual spontaneous baryogenesis. Let us denote the baryon asymmetry by Y_{osc} . As the axion has initially large quantum fluctuations at super-horizon scales, Y_{osc} has isocurvature fluctuations at large-scales, which is the counter part of the baryonic isocurvature fluctuations in the spontaneous baryogenesis in the slow-roll regime. In our case, the size of the baryonic isocurvature pertur-

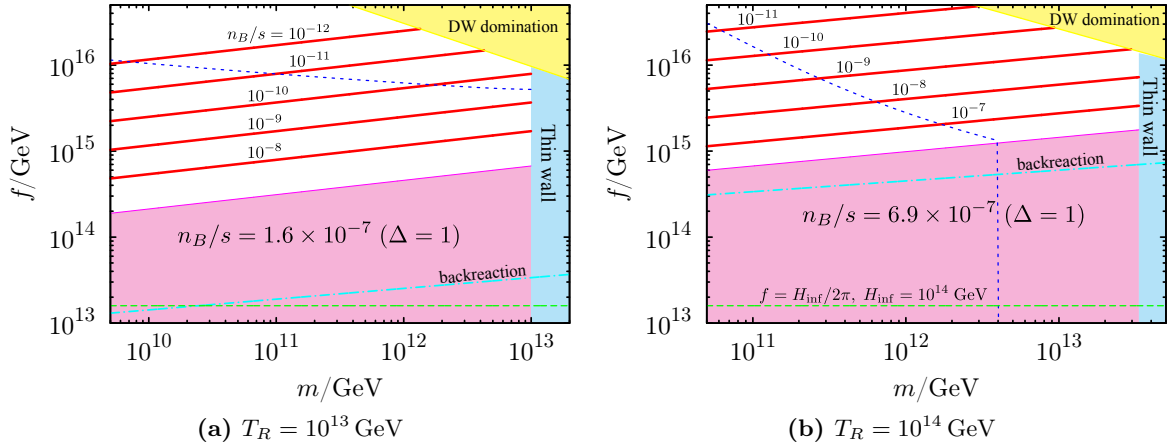


Figure 3. Same as figure 2 but for $T_R = 10^{13}$ GeV (left panel), 10^{14} GeV (right panel). The solid red lines correspond to the contours of $n_B/s = 10^{-12}$ – 10^{-7} from left to right and the magenta shaded regions correspond to the maximal value, 1.6×10^{-7} (left panel) and 6.9×10^{-7} (right panel). The dash-dotted cyan line represents the lower bound from the back reaction and the yellow-shaded region is ruled out from domain wall domination.

bations, $\delta Y_{\text{osc}}/Y_{\text{osc}}$, is expected to be of order unity. This can be understood by noting that the chemical potential can be either positive or negative, depending on which vacuum the axion is rolling down to. After the commencement of oscillations, the scalar wave dynamics between walls are random and complicated. In particular, the spatially averaged effective chemical potential is zero, and no fluctuations at super-horizon scales are induced by the dynamics in the scaling regime. Therefore, Y_{osc} and its fluctuations at large scales receive the main contribution from the domain wall formation when $H \sim m$.

Finally, the domain-wall dynamics toward the scaling regime will also induce the baryon isocurvature perturbations. For domain walls to be formed, or more precisely, for infinitely long domain walls to be formed, the probabilities to realize the two vacua must be comparable, but they do not have to be exactly equal to each other. It implies that, when domain walls are formed, the spatial volume of one of the vacua is generically larger (or smaller) than that of the other by (at most) a few tens of percent. The ratio of the two volumes will quickly converge to unity as the domain-wall network approaches the scaling evolution. This is because the two vacua are degenerate in energy and there is no preference to one over the other once the scaling regime is reached. In this process toward the scaling regime, there is an overall transition from one of the vacua to the other, which similarly induces the baryon asymmetry. Let us denote the asymmetry by $Y_{\text{DW,form}}$. As the bias of the spatial volumes is induced by the quantum fluctuations of the axion, $Y_{\text{DW,form}}$ has isocurvature fluctuations at large scales. The magnitude of $Y_{\text{DW,form}}$ is expected to be comparable to Y_{osc} , and the sign is opposite. So, there is a partial cancellation, but in general, there is no exact cancellation. For our scenario to work, both Y_{osc} and $Y_{\text{DW,form}}$ must be sufficiently suppressed, since otherwise the baryonic isocurvature perturbations and their non-Gaussianity, would be too large to be consistent with observations.

The baryon asymmetry generated at the domain-wall formation can be suppressed as follows. If the lepton-number violation processes are in equilibrium between the formation and annihilation of domain walls, the initial asymmetry Y_{osc} and $Y_{\text{DW,form}}$ can be washed out.

This is the case if the reheating temperature is higher than $\sim 10^{13}$ GeV. For lower reheating temperature, the lepton-number violating processes remain decoupled all the time. Then, Y_{osc} and $Y_{\text{DW,form}}$ can be suppressed if the lepton-number violating rate is much smaller than the Hubble parameter at the domain formation.

In our numerical calculations, we have estimated $|Y_{\text{osc}}| \sim |Y_{\text{DW,form}}|$ by following the motion of a test domain wall which goes through a fixed position at $H = m$. Using the test domain wall as background classical field evolution, we have calculated the induced baryon asymmetry in the plasma by solving the Boltzmann equation. By doing so, we effectively evaluate $|Y_{\text{DW,form}}|$ (or $|Y_{\text{osc}}|$) at the formation, neglecting the complicated dynamics of the scalar waves and domain-wall evolution, which do not have any preference to baryons over anti-baryons.

The current constraint on the matter isocurvature perturbation \mathcal{S} from the Planck observation reads $\mathcal{P}_{\mathcal{S}} < 8.7 \times 10^{-11}$ [40]. Using the fact that baryon isocurvature perturbation is written as $\mathcal{P}_{\mathcal{S},b}^{1/2} \sim \delta\Omega_b/\Omega_m \simeq 0.15(\delta\Omega_b/\Omega_b)$, we obtain the constraint on the baryon isocurvature perturbations as $\delta\Omega_b/\Omega_b \lesssim 6 \times 10^{-5}$. Since the baryons produced by the axion coherent oscillations or domain wall dynamics toward the scaling regime is $O(1)$ in the present scenario, $\Omega_{b,\text{osc}}/\Omega_b \lesssim 6 \times 10^{-5}$ must be satisfied in order to avoid too large isocurvature perturbations. Then, we obtain the constraint on the resultant baryon asymmetry induced by the coherent oscillations,

$$\frac{n_{B,\text{osc}}}{s} = \frac{n_B}{s} \frac{\Omega_{b,\text{osc}}}{\Omega_b} \lesssim 5 \times 10^{-15}, \quad (3.16)$$

and a similar bound on the asymmetry induced by the domain wall dynamics toward the scaling regime. This upper bound is shown by a dotted (blue) line in figures 2 and 3.

The baryon isocurvature perturbations may be further suppressed in some particular situations. For example, one can consider a case in which the $U(1)_{B-L}$ gauge symmetry is still unbroken at the onset of the axion oscillation and it gets spontaneously broken before the domain wall annihilation. In such a case, there is no lepton number violating operators and no baryon asymmetry is induced until the spontaneous break down of the $U(1)_{B-L}$ symmetry. If the domain wall network already follows the scaling law when the $U(1)_{B-L}$ symmetry gets spontaneously broken, no baryon isocurvature perturbation is generated by the coherent oscillations or domain wall dynamics. Interestingly, cosmic strings are formed after the spontaneous breaking of $U(1)_{B-L}$ and they can emit a sizable amount of gravitational waves which can be within the reach of future observations [41].

4 Discussion and conclusions

Collapsing domain walls are cosmological sources of gravitational waves [12–14]. The gravitational wave spectrum is peaked at a frequency,

$$f_{\text{peak}} \simeq 160 \text{ kHz } \xi^{-1/2} \left(\frac{g_*}{106.75} \right)^{1/6} \left(\frac{T_X}{10^{12} \text{ GeV}} \right), \quad (4.1)$$

corresponding to the Hubble horizon scale at the domain wall annihilation [15]. Here ξ and T_X are defined as

$$\xi = \min \left(1, \left(\frac{\Gamma_I}{H_{\text{ann}}} \right)^{2/3} \right), \quad T_X = \min(T_R, T_{\text{ann}}). \quad (4.2)$$

For successful baryogenesis, T_X must be higher than 2×10^{11} GeV, and so, the peak frequency is at $\mathcal{O}(100)$ kHz or higher, which is too high to be detected by near future observations. We note however that there have been proposed several new detection techniques with the sensitive frequency region around MHz [42, 43], which may be able to probe gravitational waves produced in our scenario.

So far, we have considered the L -number violating processes mediated by heavy right-handed neutrinos in the seesaw mechanism. Other types of the baryon/lepton violating operator is also possible and the corresponding decoupling temperature for the baryon/lepton violating processes could be lowered. One of the examples is the R-parity violating operator,

$$W = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k \quad (4.3)$$

in the supersymmetric Standard Model. In this case, the interaction rate for the L -violating processes scales as $\Gamma \propto T^5$ for $T \ll m_{\tilde{\ell}}$ and $\Gamma \propto T$ for $T \gg m_{\tilde{\ell}}$, where $m_{\tilde{\ell}}$ is the slepton mass. For instance, if we take $\lambda \sim 10^{-8}$ and $m_{\tilde{\ell}} \gtrsim 10^9$ GeV, the L -violating process marginally reaches equilibrium and soon decouples at $T_{\text{dec}} \sim 10^9$ GeV. Since the maximal possible value of lepton asymmetry is roughly given by $n_L/s \sim 0.1 T_{\text{dec}}/M_P$ from the first equality in (3.7), successful baryogenesis is possible with $T_{\text{ann}} \sim 10^9$ GeV. In this case, the peak frequency of the gravitational waves from the domain wall annihilation can be within the sensitivity range of the ground-based detector such as advanced-LIGO [44] and KAGRA [45, 46]. For instance, if we take $T_R \sim m \sim 10^9$ GeV and $f \sim 10^{13}$ GeV, domain walls dominate the Universe at the annihilation and the peak frequency falls in the sensitivity range of these experiments. A naive order-of-magnitude estimate suggests, however, that the signal strength is a few orders of magnitude smaller than the predicted sensitivity, and either some deviation from the scaling regime or further improvement of the sensitivity would be necessary to directly probe such signals.

In this paper we have proposed a baryogenesis scenario using axion domain walls. Axion domain walls are produced if the axion acquires sufficiently large quantum fluctuations during inflation or if it initially stays sufficiently close to the local maximum. While no net baryon asymmetry is produced in the scaling regime, collapsing axion domain walls produce a large enough baryon asymmetry to explain the observed value. This is because the energy bias between the two vacua, and therefore between baryons and anti-baryons, becomes relevant only when domain walls annihilate. In particular, baryon isocurvature perturbations can be significantly suppressed in our scenario, either because the asymmetry produced by the initial field configurations is washed out by the L -number violating interactions in equilibrium, or because the L -number violating interaction is simply suppressed at the domain wall formation. In some parameter region, baryon isocurvature perturbations and their non-Gaussianity are suppressed, but non-negligible, which may be detected by future observations. Our scenario works together with high-scale inflation which predicts a large tensor-to-scalar ratio within the reach of future B-mode observations. The required relatively high reheating temperature can be realized in high-scale inflation more easily. This should be contrasted to other spontaneous baryogenesis scenarios in which the inflation scale is severely constrained by the isocurvature perturbations. Although we have focused on the axion domain wall throughout this paper, our analysis can also be straightforwardly applied to a wide class of domain walls such as the Standard Model Higgs domain wall [47, 48].

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